hep-ph/9910397
RM3-TH/99-12

TESTS OF THE STANDARD MODEL AT HERA

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ABSTRACT

We review how experimental data collected at the HERA lepton-hadron collider have improved our theoretical and phenomenological understanding of the standard model, and specifically of its QCD sector.

Invited talk given at the
EPS Conference on High Energy Physics
Tampere, Finland, July 1999
to be published in the proceedings

October 1999

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Tests of the Standard Model at HERA

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Abstract
We review how experimental data collected at the HERA lepton-hadron collider have improved our theoretical and phenomenological understanding of the standard model, and specifically of its QCD sector.

1. Factorization

HERA is unique as a lepton-hadron collider. The measurement of lepton-hadron scattering cross sections allows for detailed tests of the standard model thanks to the factorization property of many hard QCD processes. The perturbative computation of the hard elementary process, and in particular strong radiative corrections to it, allows a detailed test of both the electroweak and strong sectors of the theory. Whereas of course electroweak tests are generally not competitive with the cleaner setting of lepton colliders such as LEP, QCD tests at HERA allow reaching kinematical regions which could not be attained in fixed–target experiments, while offering a cleaner setting in comparison to hadron colliders such as the Tevatron.

1.1 The electroweak subprocess
The recent determination of the charged-current contribution to the cross-section over a wide enough range of Q^2 allows a simultaneous extraction of the Fermi constant G_F and the W mass[1]; the ZEUS collaboration for instance gets $M_W = 80.9\,^{+4.9}_{-4.6}\,(\mathrm{stat.})\,^{+5.0}_{-4.3}\,(\mathrm{syst.})\,^{+1.3}_{-1.2}\,(\mathrm{pdf.})$. Notice that the last source of error is due to the choice parton distributions. Assuming the correctness of the standard model and the ensuing relation between M_W and G_F leads to a value $M_W = 80.5 \pm 0.4$, much better than the above model independent one. Even though this is inevitably not competitive with the LEP determination, it provides a nice consistency test.

1.2 Testing QCD vs. using QCD
Because of the overwhelming success of perturbative QCD[2], fundamental tests of its correctness are these days relatively less interesting in comparison to the precise determination of its free parameters. In practice, this includes the strong coupling α_s but also all quantities which can not be calculated perturbatively, such as parton distributions. An accurate knowledge of these quantities is a necessary input to the determination of any hadronic process, and is thus a crucial ingredient for e.g. LHC physics. An accurate determination of QCD backgrounds to new physics is also needed. Recent progress involves more accurate determinations of parton distributions (see Sect. 2), and widening the perturbative domain, by learning how to treat processes with many large scales (Sect. 3) and extending factorization theorems to less inclusive processes (Sect. 4).

2. Structure functions and parton distributions

A striking success of perturbative QCD is the prediction of scaling violations of structure functions. The proton structure function $F_2(x, Q^2)$ in particular is measured at HERA for values of Q^2 extending up to 10^4 GeV^2 and $\frac{1}{x}$ up to 10^5. Detailed analyses[3] show excellent agreement between the data and the next-to-leading order QCD prediction throughout this region. Note that even though comparing data with theory requires a fit of parton distributions, the scale dependence is then entirely predicted. This is to be contrasted with model parametrizations, where the full x, Q^2 dependence of the data is fitted by a given functional form. Two features of these analyses[3] are worth noticing. First, excellent agreement is obtained with a value of the strong coupling fixed at the world average $\alpha_s(M_z) = 0.118$, in contrast to earlier indications that α_s from scaling violations should be smaller. Also, contrary to expectations, next-to-leading order scaling violations agree very well with the data even at the boundaries of the kinematic region, in particular at moderate Q^2, very large, and very small x (see Sect.3).

2.1 Errors on parton distributions
The succesful description of structure functions and their scaling violations within QCD suggests that they can be reliably used to determine parton distributions. Indeed, these data provide the strongest constraints on current parton sets[4], while less inclusive data (Sect. 3.2) give additional constraints.

Currently available parton sets do not come equipped with errors. However, a recent study[5]

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shows that if the W and Z production cross-section at Tevatron is computed using different parton sets, the variation of the results is already comparable to the experimental errors (see also the determination of M_W above). However, independent parton determinations share many theoretical assumptions, and simply varying the pdf cannot provide a reliable error estimate. A better estimate can be obtained by scanning the parameters of a given set[5, 6], but the outcome then cannot be folded into subsequent analyses. An interesting suggestion[7] to overcome these problems is based on the idea of giving the results as a probability functional $\mathcal{P}[f]$ (rather than a fixed parameterization), which can then be determined by Bayesian inference in a monte carlo approach. The result can then be ported to subsequent calculations. Determinations of pdfs based on this approach are currently under way[8].

2.2 PDFs from non-inclusive processes

Specific processes can provide stronger constraints on individual pdfs than global fits based on structure function data. Such information will be copiously collected by future experiments such as COMPASS. A recent example is the determination of the gluon distribution[9] from the dijet cross-section through its photon-gluon fusion component. Another example is the determination of the flavor asymmetry in the nucleon sea $\bar{d}(x) - \bar{u}(x)$ [10], where parent current quarks are identified by their preferred fragmentation by tagging mesons in the final state. Although this measurement is not competitive with that from Drell-Yan[11], similar, more refined measurements in future experiments could provide valuable constraints. The relevance of such measurement is highlighted by the fact that insufficient knowledge of the gluon distribution and the flavor asymmetry of the sea had been respectively suggested[6, 12] as possible explanations of the excesses of high p_T jets at the Tevatron and of high Q^2 events at HERA which had been initially interpreted as possible indications of new physics.

3. QCD at small x

Because the total center-of-mass energy of $\gamma^* - p$ collision is $W^2 = \frac{1-x}{x} Q^2$, the small-x region of deep-inelastic scattering has been accessed for the first time at HERA.

3.1 Double Asymptotic Scaling

Perturbative QCD at leading and next-to leading order predicts[13, 14] that the gluon distribution, and thus the structure function $F_2(x, Q^2)$ at small x and large Q^2 should asymptotically depend on the single variable $\sigma = \sqrt{\ln x \ln \ln Q^2}$, exponentially rising with σ with slope $\gamma = \sqrt{2C_A/\beta_0}$ (double scaling).

This prediction is beautifully borne out by the HERA data, contrary to the pre-HERA expectation that the rise should be quenched by non-perturbative effects, or substantially modified by higher order corrections (see Sect. 3.2). The predicted and observed slopes agree to about 10%, which is the size of the expected subasymptotic corrections in the HERA region[15]. This tests the fundamental nonabelian nature of the gauge interaction. The largeness and universality of small x scaling violations and the success of the NLO computation at HERA suggest that this is an optimal region to determine α_s, since the dependence on the parton distributions will be minimal. This is borne out by a preliminary analysis based on 1995 HERA data[16]. An extraction based on current data would be very competitive with other recent determinations.

3.2 Small x scaling violations

The double scaling rise of F_2 is driven by the (rightmost) simple pole of the LO and NLO anomalous dimensions. However, higher order contributions are known to display higher order poles, and might be expected to modify double scaling. The coefficients of the leading singularities to all orders in α_s in the gluon sector can be extracted from the BFKL equation[17], and are also known in the quark sector[18]. If a summation of such contributions is included in the computation of scaling violations, the agreement with the HERA data deteriorates[19]. Likewise, the subleading correction to these coefficients can be extracted[20] from the recently determined[21] subleading corrections to the BFKL kernel. They are extremely large (and negative), and their ratio to the leading coefficient grows linearly with the perturbative order. This perhaps explains the failure of the LO summation, but makes the success of the unimproved NLO computation all the more puzzling.

It can be shown that this bad large-order behavior of the summation of small x corrections to anomalous dimensions is generic, and can be removed by a suitable reorganization of small x perturbation theory[22]. The reorganized expansion has a stable asymptotic behavior, but still leads to large subasymptotic corrections with a poorly behaved perturbative expansion. It turns out that these problem can in large part be cured by imposing suitable matching conditions between large and small x expansions, in particular embodying momentum conservation. The success of standard two-loop evolution can thus be accommodated within this framework[23].

Several more ways of dealing with the bad behavior of the small x expansion have been suggested, based on various resummations of formally subleading corrections[24]. It remains to be seen whether any of these approaches can lead to succesful phenomenology. A firmer grasp of the pertinent phenomenology will be required in order to reliably evolve parton distributions to the large Q^2, small x region relevant for LHC phenomenology.

3.3 Energy evolution

The summation of small x contributions to scaling

violations corresponds to a summation of leading $\ln\frac{1}{x}$ contributions to the deep-inelastic cross section. Such a summation can be more directly obtained by solving an evolution equation in $\frac{1}{x}$, i.e. in in the CM energy of the process (BFKL equation). This is relevant for processes where there is considerable energy evolution but little Q^2 evolution, such as deep-inelastic forward jet production, where the jet transverse energy and photon vituality are similar, $k_T^2 \sim Q^2$, but the momentum fraction carried by the jet is large while Bjorken $x \ll 1$[25]. One expects then a resummation of $\ln\frac{1}{x}$ to afford better phenomenology than the usual $\ln Q^2$ resummation. This expectation is not borne out by recent HERA data[26], which appear to be adequately described by standard Q^2 evolution, provided only one allows for a resolved photon component whenever $k_T^2 \gtrsim Q^2$.

4. Diffraction and leading hadrons

Leading hadron processes are defined by tagging a hadron in the target fragmentation region. Diffractive processes are then leading proton (LP) events with the further requirement that the LP carries a large fraction of the incoming hadron's momentum, i.e. with a rapidity gap between the LP and the remnant of the final state. Surprisingly, diffractive events at HERA make up for as much as 10% of the total structure function F_2. An understanding of diffractive p-p events is important because they are an important background to standard Higgs production.

Within perturbative QCD the leading hadron cross-section can be proven to satisfy a factorization theorem[27] which allows expressing it in terms of a hard coefficient function and a fracture function[28], defined as the differential component of the standard structure function in the presence of a leading hadron with the given kinematics. Fracture functions satisfy the standard QCD evolution equations. A phenomenological analysis of HERA diffractive and leading proton data[29] shows that the predicted universality and scale dependence of fracture functions are well reproduced. The problem of computing (rather than fitting) fracture functions from first principles has attracted considerable theoretical attention[30].

5. Conclusion

HERA has played for QCD a similar role as LEP for the electroweak sector of the standard model. In general, perturbative computations lead to excellent phenomenology; this however seems to happen even beyond the regions were one might expect it.

Acknowledgement: I thank G. Passarino for convening this lively session and for inviting me to put HERA physics in the context of the standard model, and G. Altarelli and R. Ball for useful comments.

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